GUIDING ADAPTATION: THE USE OF FRAMEWORKS IN CLIMATE CHANGE VULNERABILITY ASSESSMENTS ON AN ECOSYSTEM SCALE

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Abstract

Global warming of 1.5 degrees Celsius is likely to be reached by the mid-20th Century and sea-levels will continue to rise through 2100, even with immediate action. In order to respond to a changing climate and its effects, adaptation planning on a large scale must occur. In order to do this, the first step in a comprehensive risk assessment process is to assess vulnerability. While this is done with different scopes and scales in mind, climate change vulnerability assessments (CCVAs) of ecosystems take into consideration vulnerability of species, human systems, and areas. CCVAs on an ecosystem scale are growing in number and evidence is mounting that they may be outnumbering species-specific CCVAs in some areas. However, challenges that plague wide scale adoption of ecosystem-based CCVAs stem from a lack of institutional and scientific agreement on the operational definition of vulnerability and its terms. How this definition translates to an assessment framework and methodology plays a large role in the outcome of an assessment. A review of CCVAs for ecosystems shows that conceptual frameworks are not currently being used consistently and that when they are used, framework design varies. While some CCVAs looked to the IPCC as a source of a framework or operational definition of vulnerability, the published definition from this one source has changed over time. This has led to different interpretations of how to operationalize vulnerability even in those CCVAs citing the same source. Reviewed CCVAs also cited a number of other sources for frameworks, if they used one at all, which contributes to large variability in how vulnerability is defined and weighted for the purposes of assessment. This leads to different methodologies, data collection, and ultimately issues in data sharing and integration.

Keywords*: Climate Change, Adaptation, Vulnerability, Assessment, Framework, Methodology*

Introduction

The 2018 Special Report recently published by the IPCC states with high confidence that global warming of 1.5 degrees Celsius is likely to be reached between 2032 and 2052.[1] Even if warming is kept to 1.5°C, sea level rise predicted for the 21st century is largely locked in due to irreversible ice sheet loss and instability.[2] This report is very troubling to scientists and policymakers that have been working to establish policy goals that will aid in keeping that temperature threshold from being reached. Even with agreement within the scientific community about the danger, disagreement on the severity or timing of warming by key GHG producers also continues to trouble this process. The uncertainty surrounding the position of key players such as the United States in both the Paris Agreement and the underlying UN Framework on Climate Change has made mitigation policy, both domestic and international, more and more difficult. Moreover, a report also released this year by 13 U.S. Federal Agencies recognizes numerous areas of climate-related risk.[3] Specifically the report states that "While mitigation and adaptation efforts have expanded substantially in the last four years, they do not yet approach the scale considered necessary to avoid substantial damages to the economy, environment, and human health over the coming decades."[4]

As the threat of greater warming continues to increase without action, countries and individuals will only need to increase their focus on adaptation methods. While some areas or communities have already seen measurable impacts of a changing climate, ranging from severe

[1] IPCC. "Summary for Policymakers". Global Warming of 1.5°C. an IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. (World Meteorological Organization, 2018), 6
[2] Ibid, 9
[3] U.S Global Change Research Program. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. (2018), 1-186
[4] Ibid, 13

storm events to drought conditions, other areas have an unknown level of vulnerability. This is because either assessments of the impacts of climate change have not yet been completed or there is not sufficient data to thoroughly assess the full range of impacts.[5] Climate change is predicted to have measurable direct effects such as changes in rainfall or temperature.[6] Assessing the effects of these changes on a species or area sometime requires availability of climate or weather data, whether real or modeled. Challenges in assessing vulnerability can be related to data availability and completeness or integration of data from different spatial scales or producers to cover the desired area.[7] Indirect effects of climate change also need to be considered and can be numerous and dependent on the scale and detail of an assessment.[8] These indirect impacts could include impacts on human health due to changes in disease transmission or spread of allergens or the impact of changing climate on suitable ranges for keystone species.[9]

Assessing Vulnerability

When looking to assess vulnerability of natural resources and systems, a common use of a vulnerability assessment is to determine the level of vulnerability of a certain species or group of species and use this to inform management actions to improve population health or habitat health. Vulnerability assessments can play a critical part in a comprehensive risk assessment or be used as a tool to plan or guide investments in conservation. For example, they have been used by the International Union for Conservation of Nature (IUCN) to inform their Red List which

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[5] Suraje Dessai, Xianfu Lu, and James S. Risbey. "On the Role of Climate Scenarios for Adaptation Planning." *Global Environmental Change Part A: Human & Policy Dimensions* 15, no 2 (2005): 87, doi:10.1016/j.gloenvcha.2004.12.004.
[6] IPCC. “Summary for Policymakers” 6.
[7] Dessai, Lu, and Risbey. "On the Role of Climate Scenarios." 87.
[8] Ibid, 88.
[9] Tanja Wolf, Wen-Ching Chuang, and Glenn McGregor, “On the Science-Policy Bridge: Do Spatial Heat Vulnerability Assessment Studies Influence Policy?” *International Journal of Environmental Research and Public Health* 12, (2002): 13322, doi:10.3390/ijerph121013321.

designates threatened species.[10] In recent years, the design of these assessments have been increasingly motivated by the need to better understand how a vulnerable species may respond to climate or non-climate changes on their range.[11] Major conservation funders and policy makers have recognized climate change as a risk-factor to global biodiversity, hence an important component of vulnerability.[12] This has led to species-specific climate change vulnerability assessment methodologies like the NatureServe Climate Change Vulnerability Index (CCVI), and the US Forest Service System for Assessing Vulnerability of Species (SAVS).[13]

However, the use of vulnerability assessments to determine how human populations or infrastructure will be affected by climate change has also been growing in recent years.[14] More localities want to know their level of risk to a changing climate and the scale of impacts.[15] What has emerged are numerous different approaches to assessing vulnerability to climate-related risks that focus on either infrastructure, operations, species, natural or nature-based features, or overall area risks.[16] It is becoming increasingly clear through research and observation that human responses to climate change are linked to environmental changes that affect species ability to adapt to their environments in a changing climate.[17] This suggests that the evaluation of vulnerability of humans, ecosystems, and species to climate change should be done in conjunction. Especially when the interactions between native species, humans, infrastructure,

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[10] Kurt A. Johnson. "Climate Change Vulnerability Assessment for Natural Resources Management: Toolbox of Methods with Case Studies" U.S. Fish and Wildlife Service, 2014.
[11] Dessai, Lu, and Risbey. "On the Role of Climate Scenarios." 87.
[12] Joshua Steven Reece et al. "A Vulnerability Assessment of 300 Species in Florida: Threats from Sea Level Rise, Land Use, and Climate Change." PLoS ONE 8, no. 11 (November 2013): 1. doi:10.1371/journal.pone.0080658.
[13] Kurt Johnson. "Climate Change Vulnerability Assessment for Natural Resources Management." 10.
[14] Dagmar Schröter, Colin Polsky, and Anthony Patt, "Assessing Vulnerabilities to the Effects of Global Change: An Eight Step Approach", Mitigation and Adaptation Strategies for Global Change 10, (2005): 573–596
[15] Ibid, 575.
[16] Ibid, 580.
[17] Sean L. Maxwell, Oscar Venter, Kendall R. Jones, and James E. M. Watson. 2015. "Integrating Human Responses to Climate Change into Conservation Vulnerability Assessments and Adaptation Planning." Annals of the New York Academy of Sciences 1355 (1): 98–116. doi:10.1111/nyas.12952.

and natural systems will interact and respond to climate changes differently due to differences in how each area is structured as a unique ecosystem.

In fact, "place-based" vulnerability assessments have been recognized as addressing the issue of different areas having unique hazards when exposed to the same climatic changes.[18,19] They view human, systems, and ecosystem-services as an "ensemble" and pay mind to the many interconnections that play a role in overall vulnerability and risk.[20] The growth of "place-based" assessments and recognition of their elevation among available tools for conservation managers begs the question of how these assessments should be designed and guided to be the most useful in different scales and for different management purposes. Some believe that an integrated framework is essential in this respect because of the fact that assessments will span disciplines and take years to complete.[21] Therefore, a general but integrated framework serves the purpose of general guidance to orient these assessments on a common scale and provides better understanding of both the data informing the vulnerability determination and assumptions used in getting this data.[22]

Vulnerability can be defined in many ways but for purposes of climate change vulnerability it is defined as "the extent to which a species, habitat, or ecosystem is susceptible to harm from climate change impacts."[23] Climate change vulnerability assessments (CCVAs) have been a useful tool in identifying disaster vulnerability even prior to their use in managing for

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18 Dagmar, Polsky, Patt, "Assessing Vulnerabilities to the Effects of Global Change", 574.
19 Turner et al. "A Framework for Vulnerability Analysis in Sustainability Science." *Proceedings of the National Academy of Sciences of the United States of America 100*, no. 14 (2003): 8074-8079. doi:10.1073/pnas.1231335100.
20 Ibid, 8080
21 Dagmar, Polsky, Patt, "Assessing Vulnerabilities to the Effects of Global Change", 574.
22 Ibid, 574.
23 Schneider, S.H., et al. "Assessing key vulnerabilities and the risk from climate change." *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, et al. (eds.), Cambridge University Press, Cambridge, UK: 779-810.

adaptation or loss and damage to climate-related effects.[24] However, they have since been established as a key tool in developing climate adaptation plans, whether national or local. The fields of disaster adaption and climate change adaptation have been studied and reviewed to show a significant amount of overlap in their purposes.[25] As such, design of vulnerability assessments for either purpose can share some content or structure. However, a common issue for both is the lack of framework and ability to integrate into a larger assessment plan or scale, accordingly.[26] Without this ability, stakeholders may face difficulty in data sharing or find themselves conducting superfluous or overlapping assessments.

While there are differences in the purpose and desired outcomes of disaster risk assessments and climate change vulnerability assessments, the two share enough in common that synergies between the two approaches could be utilized.[27] Recommendations have been made to strengthen the links between climate change adaptation and disaster risk reduction communities "through the specification of common approaches to risk assessment methods."[28] To begin to approach a common method involves a comprehensive framework and a base scale that involves both ecosystems and societies where the two fields interact. One example is how natural features such as marshland provide ecosystem services, serve as key habitat, and also provide regional benefit in the way of storm surge wave energy absorption.[29] When looking at assessing vulnerability to disaster and loss, along with assessing vulnerability of an integrated area made

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[24] Solecki, William, Robin Leichenko, and Karen O'Brien. "Climate Change Adaptation Strategies and Disaster Risk Reduction in Cities: Connections, Contentions, and Synergies." *Current Opinion in Environmental Sustainability* (2011) 3 (3): 136
[25] Ibid, 136
[26] Ibid, 137
[27] Solecki, Leichenko, and O'Brien. "Climate Change Adaptation Strategies and Disaster Risk Reduction" 136
[28] Ibid, 137
[29] Bridges, Todd,S., Paul Wagner, Kelly Burks-Copes, Matthew Bates, Zachary Collier, Craig Fischenich, Joe Gailani Z., et al. "Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience," US Army Corps of Engineers Final Report, 2015.

up of humans, species, and structures, defining the assessment by area begins to emerge as the only scope to appropriately capture all necessary interactions and variables.

Ecosystem-Based Approach

The Ecosystem-Based Approach (EbA) emerges as an ideal balance between informing human adaptation needs and protecting nature/natural services in terms an appropriate scale and scope for CCVAs. The term EbA was recognized by the IUCN in 2009, added as an adopted term at the Convention on Biological Diversity (CBD) 10th Conference of Parties (COP), and included in the UNFCCC prior to COP17[30,31] While there are many working definitions of EbA, the one most used is the 2009 CBD working technical report definition of "The use of biodiversity and ecosystem services (BES) as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change."[32]

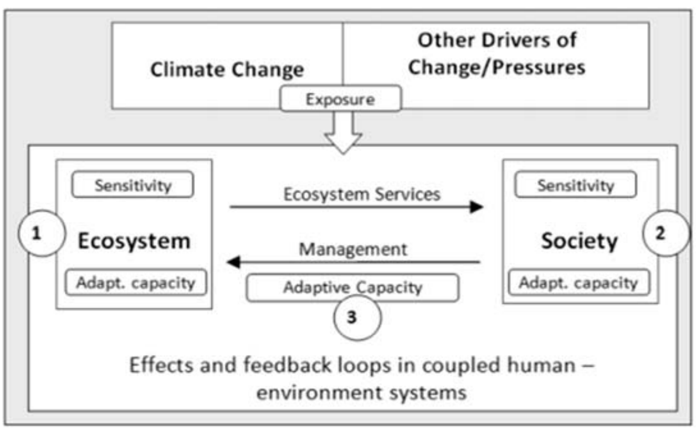

Figure 1: Effects and Feedback loops in Coupled Human-Environment Systems from Locatelli et al. 2008.

Figure 1 adapted from Locatelli et al 2008 shows the interaction between an ecosystem and society and how climate change exerts pressures on the interaction of these two systems.[33] EbA involves multi-stakeholder approaches to addressing both ecosystem services and how people

[30] Andrade. "Principles and Guidelines," 2.
[31] Ibid, 2.
[32] Convention on Biological Diversity. "Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change, Montreal." Montreal, Technical Series No. 41 (2009): 9.
[33] Locatelli, Bruno, Markku Kanninen, Maria Brockhaus, Carol Pierce Colfer, Daniel Murdiyarso, and Heru Santoso. "Facing an uncertain future: How forests and people can adapt to climate change." (2008): 29.

benefit in multiple ways from the ecosystem.[34] There are numerous stakeholders that drive the interactions in the feedback loops of coupled systems and numerous points of focus for possible assessment.[35] However, recognition of these connections in an ecosystem presents the opportunity to begin assessments at a scale suitable to serve multiple assessment purposes with climate and area sensitivity data able to be shared and scaled.

EbA recognizes that Natural and Nature Based Features (NNBF) can provide coastal and climate resilience as well as provide ecosystem services.[36] When considering vulnerability to climate change, a common request has been for synergistic approaches that cross-cut multiple areas and among stakeholders.[37] Specifically, EbA is an opportunity to act on these needs and a work towards a UNFCCC goal to "Build the capacity to institutionalize ecosystem-based approaches for adaptation at different levels (e.g. involving key stakeholders at the local and district levels in planning and developing scenarios and vulnerability assessments)."[38] EbA has gained momentum and many stakeholders have worked together to establish principles, metrics, indicators, and guidelines for the adoption and integration of EbA into adaptation strategies.[39,40,41] Guidelines released in 2012 have helped connect EbA to the Cancun Adaptation Framework Principles that were adopted at the UNFCCC 16th COP.[42] This along with other work done on highlighting the objectives and benefits of the EbA accomplishes the first step in recommendations made by researchers concerning developing a monitoring and evaluation

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34 Locatelli et al. "Facing an uncertain future." 29.
35 Ibid, 30
36 Bridges et al. "Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience," 2015.
37 United Nations Framework on Climate Change. "Report on the Technical Workshop on Ecosystem-Based Approaches for Adaptation to Climate Change."3–14 June 2013: 19.
38 Ibid, 18.
39 Ibid, 11.
40 Margaret Spearman and Radhika Dave. "A Review of Monitoring and Evaluation Approaches for Ecosystem-Based Adaptation." Conservation International—Africa Biodiversity Collaborative Group. (2012): Pp. 28.
41 Andrade. "Principles and Guidelines," 2.
42 Ibid, 2.

system to be able to evaluate success under the approach.[43]

Utilizing a Framework

However, outside of general guidance on the approach itself and case studies, EbA has not yet been considered as a unifying approach to the undertaking of vulnerability assessments. EbA by definition is only a part of a comprehensive adaptation strategy, but its success and adoption into conservation plans highlights the need to look at vulnerability to climate change effects on an ecosystem scale in order to capture all the relationships between human systems, ecosystems, and ecosystem-services. The varied nature of specific adaptation needs and risks posed to each ecosystem (or area) requires a flexible process of responding to these needs. CCVAs are designed by varied stakeholders that are seeking to address different goals with their comprehensive risk management or long-term management plans. Pushing an ecosystem approach increases the likelihood that assessments are oriented in a way to truly capture the interactions at play.[44] However, in order to make this information scalable and able to be integrated with other assessments, there needs to be a top-down management approach to synergize processes, indicators, and metrics used in these approaches.

A top-down approach to CCVAs utilizing a theoretical framework addresses the need to provide guidance on how ecosystem components interact to reach a total vulnerability rating for an area. The goal is to provide guidance on how climate change vulnerability is viewed in the community and what factors inform vulnerability without being overly prescriptive.[45] Using terms like hazard, adaptive capacity, and sensitivity, for example, guide assessors to look specifically at recognized components of vulnerability while leaving the identification and

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43 Spearman and Dave. “A Review of Monitoring,” 28.
44 Maxwell et al. “Integrating Human Responses” 110.
45 Turner et al. "A Framework for Vulnerability Analysis." 8075.

weighting of components or indicators up to the assessor.[46] However, when looking at theoretical work on vulnerability there is apparently trouble converting this theoretical work to empirical use.[47] One study noted that only 14% of CCVA case studies reviewed made reference to or application of conceptual frameworks.[48] Therefore, further evaluating the use of frameworks in actual assessments of vulnerability is a needed next step if wide-scale utilization is the goal. Specifically, CCVAs utilizing an ecosystem-based approach should be looked at for their use of a comprehensive framework since this scale of assessment can serve dual purposes due to climate being a key risk factor in disaster planning and wider vulnerability and risk assessment.

CCVAs for ecosystems are an emerging field of opportunity that directly act on requests by key conservation policy makers for more integration of the full adaptation process involved in addressing climate change effects, from assessing vulnerability to enacting solutions.[49] CCVAs oriented at this scope are needed to capture interactions between species, humans, and their environments – all which will be affected by climate change.[50] However, without guidance from a conceptual framework, this scope of assessment is at risk for producing isolated results.[51,52 ,53] Literature suggests that conceptual frameworks are not being used to guide climate change vulnerability assessments for ecosystems.[54] An analysis of completed CCVAs using a two-phase literature review will aim to validate this and demonstrate the need for a framework. Use of a

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46 Turner et al. "A Framework for Vulnerability Analysis." 8076.
47 Miller et al. "Resilience and Vulnerability: Complementary Or Conflicting Concepts?" *Ecology & Society* 15, no. 3 (2010a): 1. http://www.jstor.org/stable/26268184.
48 Zou, Lele and Frank Thomalla. The Causes of Social Vulnerability to Coastal Hazards in Southeast Asia. Stockholm Environment Institute (Stockholm, Sweden 2008), 39.
49 UNFCCC, "Report on the Technical Workshop." 19.
50 Füssel, Hans-Martin. "Vulnerability: A generally applicable conceptual framework for climate change research." *Global Environmental Change* 17, no. 2 (2007): 157.
51 Wolf, S. "Vulnerability and risk: comparing assessment approaches." *Natural Hazards* 61, no 3. (2012): 1099-1113. https://doi.org/10.1007/s11069-011-9968-4.
52 Füssel, "Vulnerability: A generally applicable conceptual framework" 156.
53 Miller et al. "Resilience and Vulnerability" 15.
54 Zou and Thomalla. "The Causes of Social Vulnerability" 39.

framework when conducting vulnerability assessments of ecosystems will provide the top-down guidance needed to better adapt to climate change. It will also help move towards standardized methodology, defining of key terms, and operationalizing the definition of vulnerability which all will better allow for integration and dissemination of this important data.

Methods

To look at the application of vulnerability assessment framework design, a two-step analysis was devised. The first step of this process was to look at both the scale and scope of existing assessments. Specifically, the goal was to look at multiple data repositories for CCVAs in order to have a diverse data set and avoid sources of bias introduced by their database managers. Three databases were chosen for this first phase; the Climate Registry for the Assessment of Vulnerability (CRAVe), the Johns Hopkins Catalyst Library Database (Catalyst), and the European Climate Adaptation Platform (Climate-ADAPT). All records were evaluated by their title to look for reference to either a species of interest or an area/ecosystem of interest as the scope of CCVA. The scope in this context is defined as the dependent variable in the assessment with climate change effects defined as the independent variable. A determination was made only off of this information for inclusion into groups as part of Phase 1.

The CCVAs with a species scope were tallied in one group that was labeled “Species-Specific.” The term “Species-Specific” includes CCVAs where one or more climate related effects were looked at in relation to the effect on a species health, distribution, range, key habitat, or behavior. It also included assessments that looked at the vulnerability of a region by only assessing indicator species. Also, when considering CCVAs of infrastructure and human groups, a study was considered species-specific if the area’s vulnerability was being defined by a single indicator. This was not always a species of animal or plant but instead could be an assessment that looked at the vulnerability of power lines in a defined area. While this scenario includes an area-specific factor, the vulnerability is being measured by a single feature of interest so the decision was made to group these in the "Species-Specific" group. While a "Species-Specific" assessment can be spatially-explicit, the area of focus is defined only by its relation or importance to a single or group of species.

This is contrast with an "Ecosystem-Specific" assessment which takes into consideration human, species, and natural features into defining its area of focus. The CCVAs with an ecosystem/area specific scope were tallied into second group titled "Ecosystem-Specific". If an assessment looked at an entire industry, such as the energy industry in the UK or the transportation industry in Brazil, this was deemed Ecosystem-Specific. However, it had to be of a defined area including the reaches of that industry and consider multiple factors and interactions of operations or organisms in its scope. A review of the vulnerability of an industry on a global scale was considered out of scope. Lastly, if the title indicated that it was not a vulnerability assessment but instead a scientific paper, theory, policy, this was tallied into third group labeled "Other". If the title of the assessment was indeterminate or unreadable for any reason, the assessment was tallied under the "Other" category. This included titles not in English or titles that indicated they were test-entries or incomplete entries in the subject database.

This was then repeated with each database on each publication returned from the search criteria. The first source, CRAVe was chosen because it is a large repository of CCVAs that is collected by USGS as a part of the Interagency Land Management Adaptation Group.[55] It has a steering group that aims to make a registry that is public and includes CCVAs from non-federal

[55] USGS National Climate Change and Wildlife Science Center "Climate Adaptation Knowledge Exchange." Climate Registry for the Assessment of Vulnerability. Accessed February 3, 2019. http://crave.cakex.org/about-crave

and federal partners in the US.[56] Climate-ADAPT was chosen as a counterpart to this database but for the EU. Climate-ADAPT is run by the European Commission and European Environment Agency working as partners.[57] Two repositories of CCVAs, one hosted domestically and one hosted internationally, were purposefully chosen to identify any differences between domestic approaches and international approaches to CCVAs. Lastly, Catalyst was chosen strictly as an academic database with no connection to specifically collecting CCVAs.

The search terms for these three databases were "climate change vulnerability assessment." In the CRAVe database, all records were considered CCVAs and therefore the full database was searched. In the Climate-ADAPT database, after searching the terms the records were filtered to show only those labeled as "research and knowledge projects" and "vulnerability assessment" from the drop-down sorting menu to narrow down results to completed assessments. Lastly, in the Catalyst Database the search terms were searched in quotation marks to narrow down results to those using the full term and not just any one word. The results of these searches provided the data set for the review of assessments by title. Once the first phase was completed and all databases had been searched and tallied, the ecosystem/area specific CCVAs were sampled for case studies. 10 CCVAs were chosen at random from each database's Group II, which included the ecosystem/area specific CCVAs. With three databases sampled and 10 randomly chosen from each database, 30 total CCVAs were then evaluated in Phase II. In order to review these assessments, a worksheet was created to fill out while reviewing each assessment.

[56] USGS National Climate Change and Wildlife Science Center "Climate Adaptation Knowledge Exchange."
[57] European Environment Agency. "Climate-ADAPT." Accessed February 3, 2019. https://climate-adapt.eea.europa.eu/data-and-downloads.

Once an assessment was found to be available and fitting the criteria, its review was guided by the worksheet and included in the final results even if the design of the assessment meant that some of the worksheet categories could not be addressed. The categories of review were chosen in order to infer basic project information, infer information about assessment design, and information about assessment methodology. It was decided that the worksheet would include 9 points of comparison that spanned those mentioned categories of information. The final worksheet focused on 6 important comparison points for assessment design and 3 points of comparison for general project information. The points of comparison of the Ecosystem-Specific CCVAs asked the following about each assessment;

1) if the CCVA used a framework and who created it,

2) whether this framework followed a vulnerability formula and what it was,

3) who completed the assessment,

4) the methodology used to complete the CCVA,

5) whether it was spatially-explicit or not, and

6) whether there was a single component being evaluated as the "climate change effects" or whether it looked at multiple components.

The lead agency, title, and subject area were the areas chosen on which to collect general project information. This entire worksheet was then evaluated to see what similarities these 30 CCVAs shared. Evaluation of categories 3-6 were evaluated qualitatively to see whether any CCVAs used the same methodology and scale and whether the assessments looked at a single climate change effect or looked at multiple factors. Evaluation of categories 1 and 2 were done both qualitatively and quantitatively to see if there results in these areas were significant. The quantitative assessment was conducted to see whether CCVAs for ecosystems were using frameworks when conducting their assessments.

Results

Search of the terms “climate change vulnerability assessment” in the CRAVe, Catalyst, and Climate-ADAPT databases returned 916 publications that were reviewed for Phase I. This information is represented as a chart in **Figure 2** The CRAVe database included 240 publications that were reviewed by title for grouping by scope. 108 of these publications were deemed Species-Specific and tallied in Group I. 71 publications were deemed Ecosystem-Specific and were tallied in Group II. 61 publications were determined to be unfit for grouping as either Ecosystem-Specifc or Species-Specific and tallied as Other in Group III. The breakdown for Phase I showed 45% of the reviewed results were species-specific CCVAs. The next highest group was the ecosystem-specific CCVAs which made up 30% of the tested publications. Lastly, the Other group was tallied slightly lower at 25%. For the Catalyst database the total number of publications reviewed was 235. 15% of these were Species-Specific, 22% were Ecosystem-Specific and 63% were considered non-CCVA or Other. The Climate-ADAPT database was the third to be reviewed under Phase I and this returned 441 publications.

Phase I Results

CRAVe Database			
Species	Ecosystem	Other	Total
108	71	61	240
45%	30%	25%	

Catalyst Database			
Species	Ecosystem	Other	Total
35	52	148	235
15%	22%	63%	

Climate Adapt			
Species	Ecosystem	Other	Total
57	136	248	441
13%	31%	56%	

Figure 2: Phase I classification of results from a 3 database search for "climate change vulnerability assessments."

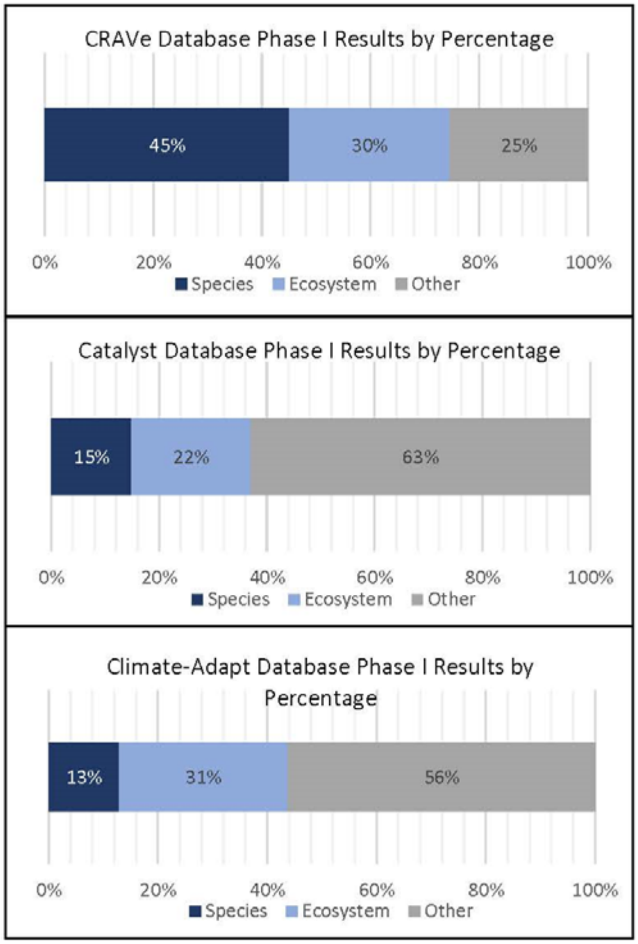

Figure 3: Results from Phase I shown as percentages of each group represented in the entire sampling

The Species-Specific group totaled 57 or 13% of the total publications, the Ecosystem-Specific group totaled 31% and the Other group totaled 56% of the 441 publications reviewed. This information is represented graphically in **Figure 3**. Once all 916 publications were grouped as Species-Specific, Ecosystem-Specific, or Other, under Phase I, the total number of Ecosystem-Specific CCVAs was determined to be 259 or 28% of the total. This data set became the subject of Phase II. 10 CCVAs from each databases' Ecosystem-Specific group were chosen at random to be reviewed under Phase II. When chosen randomly, if a publication turned out not to be a complete CCVA, not be available in English, or not accessible, another was chosen at random. This continued and entire assessments were reviewed until 30 assessments were reviewed. Phase II consisted of a detailed review of the structure and content of these 30 CCVAs that focused on how they were guided in the crafting of their methodology. This information was collected as **Table 1** and can be found in its entirety in Appendix A. Of the 6 factors assessed in the worksheet, 3 were identified as most useful for determining how and if frameworks are currently being used for ecosystem specific CCVAs. These three were 1) the use of a theoretical framework, 2) its structure, and 4) the assessment methodology. Out of 30 CCVAs that were assessed under Phase II, 17 of these assessments indicated a source for their framework or 56.7% of the total reviewed CCVAs.

The frameworks and vulnerability formulas of those assessments that did use frameworks can be seen in an abridged version of Table 1 in **Figure 4.** 13 of these assessments either indicated that they created their own framework with no reference to an existing model or they did not use one. This includes assessments that cited inspiration or influence for their framework but ultimately decided to craft one themselves. Of the 17 CCVAs that indicated they used a pre-crafted framework to guide their assessment, 6 of the CCVAs indicated that the used more than one framework. This includes assessments that referenced one framework for operational definitions of both vulnerability and its components (such as sensitivity and adaptive capacity) and another for defining the theoretical relationships between components. This was usually represented by a vulnerability formula.

Of the CCVAs that used one or more frameworks, the 11 of these assessments used different formulas for operationalizing the definition of vulnerability into a methodology. The formula represents how the components of vulnerability are weighted or combined to get a total vulnerability reading. This can also be represented as 65% of the guided assessments used different formulas for representing vulnerability. When looking at the data set of CCVAs that did not use a framework, the percent of assessments using different formulas rises to 100% when those that used no formula were not included. 6 total assessments did not use a recognizable formula to calculate their vulnerability scores. For some of these assessments, this is because the method chosen involved collecting responses of perceived vulnerability, or methods that relied on mapping and inferences to spatial data rather than modeling of component values. All of the CCVAs that did not use a framework, also did not use a formula to calculate

Figure 4

		Name	Framework	Fomula
CRAVe	2	Ecosystem Vulnerability to Climate Change in the Southeastern United States	Costanza et al. 2016	E+S=I , I+A=V
	3	Assessing Climate-Sensitive Ecosystems in the Southeastern United States	Glick et al.	E+S=I , I+A=V
	4	Assessing Climate-Sensitive Ecosystems in the Southeastern United States - Phase II	HCCVI	I+A=Res , S+Res=V
	8	Gulf Coast Vulnerability Assessment	Reece and Noss 2014	E+S=I , (I+A)/2=V
	9	Forest Ecosystem Vulnerability Assessment and Synthesis for Northern Wisconsin and	Swanston and Janowiak 2012	I+A=V
	10	American socioeconomic vulnerability: The case of the Pyramid Lake Paiute Tribe	IPCC 2001 and Füssel 2007	V=*f*(E,S,A)
Climate ADAPT	1	Water resources in Europe in the context of vulnerability	Füssel and Klein 2006, Metzger et al. 2006, and Uyttendaele et al. 2011.	E+S=I , I+A=V
	2	Adaptation to Climate Change in Europe and Central Asia Agriculture	Australian Government 2005	E+S=I , I+A=V
	3	Adaptation in water and coastal areas in Puglia, Italy	UNISDR 2009 and by IPCC 2014	H+E+VA=RR
	4	Report on Climate Analysis and Vulnerability Assessment Results in the Pilot Region (Sardinia Region)	IPCC 2014 and others	V= S(weighted) +A(weighted) / weight1+weight2
	6	An Assessment of Climate Change Vulnerability in Albania's Power Sector	Willows and Connell, 2003	V=R
	7	Adapting to a changing climate, Norway's vulnerability	IPCC 2007	V=E+S+A
	10	Climate Change Vulnerability Mapping for the Nordic Region	Preston and Stafford-Smith (2009)	V = [ES + (1–AC)] / 2
Catalyst	4	Climate change vulnerability assessment of forests in the Southwest USA	Glick et al.	V=E+S+A
	5	Climate change vulnerability assessment for the uranium supply chain in Australia	from IPCC, 2001–2007, Füssel and Klein 2006, Füssel 2007	V=*f*(E,S,A)
	9	Linkages between human health and ocean health	IPCC 2007 and Ford et. al. 2010	V=*f*(E,S,A)
	10	Income Inequality and Urban Vulnerability to Flood Hazard in Brazil	Schneiderbauer and Ehrlich 2006	V=(HxE)/A

Formula Key: V = Vulnarbility; A = Adaptive Capcity; E = Exposure; S = Sensitivity; Res = Resilience; H = Hazard; I = Impact; VA = Vulnerability Assessment; RR = Relative Risk; IA = Impact Assessment; AA = Adaptation Assessment; C = Climate Processes; S = Socioeconomic vulnerability. 2 of the 8 assessments (or 25%) that cited themselves as the source of their framework did not use a recognizable formula.

The most common source of a framework for use in an Ecosystem-Specific CCVA was the IPCC. This framework was cited in 7 of the 30 assessments as one of the frameworks used in crafting the assessment and this can be seen in **Figure 5.** However, these CCVAs that reference a framework from the IPCC make reference to three different years of publication. Even with the same international body being cited as reference for 7 of the 30 total assessments, there were still 5 different formulas used or a 70% difference in how the assessment leaders operationalized the framework. Of the formulas used, the only one that was shared with other IPCC framework inspired assessments was the formula V=*f*(E,S,A), or that Vulnerability is a function of Exposures, Sensitivity, and Adaptive Capacity. This is one of the only formulas seen in this study (of those that used them) that did not explicitly describe the relationship between the different components of vulnerability but instead just leave the relationship undefined.

Figure 5

		Name	Framework	Fomula	Methodology
CRAVe	10	American socioeconomic vulnerability: The case of the Pyramid Lake Paiute Tribe	IPCC 2001 and Füssel 2007	V=*f*(E,S,A)	Interviews
Climate ADAPT	3	Adaptation in water and coastal areas in Puglia, Italy	UNISDR 2009 and by IPCC 2014	H+E+VA=RR	Interviews + modeling
	4	Report on Climate Analysis and Vulnerability Assessment Results in the Pilot Region (Sardinia Region)	IPCC 2014 and others	V= S(weighted) +A(weighted) / weight1+weight2	modeling
	7	Adapting to a changing climate, Norway's vulnerability	IPCC 2007	V=E+S+A	modeling
	8	ICPDR Climate Change Adaptation Strategy 2018	Self - Adapted from IPCC 2007 and IPCC 2014	V+E+H=R , R=I , I=C+S and I=E	CLIMSAVE - Integrated
Catalyst	5	Climate change vulnerability assessment for the uranium supply chain in Australia	from IPCC, 2001–2007, Füssel and Klein 2006, Füssel 2007	V=*f*(E,S,A)	Interviews
	9	Linkages between human health and ocean health	IPCC 2007 and Ford et. al. 2010	V=*f*(E,S,A)	Workshop + interviews

Formula Key: V = Vulnarbility; A = Adaptive Capcity; E = Exposure; S = Sensitivity; Res = Resilience; H = Hazard; I = Impact; VA = Vulnerability Assessment; RR = Relative Risk; IA = Impact Assessment; AA = Adaptation Assessment; C = Climate Processes; S = Socioeconomic Processes; E = Emissions and Land change; I = Indicator; X = Other Factors

Interestingly, 4 of the 7 assessments that cited the IPCC chose interviews as a key component of their methodology. Outside of these 4 assessments, the only CCVAs to use interviews as part of their methodology cited either no framework or a self-created one. Outside of the term 'vulnerability' the assessments that were reviewed used a total of 15 different terms or components to describe vulnerability. This includes a component that represents 'other factors' which in the context of the study referred to responses given by interviewed stakeholders on their opinion of what affects overall vulnerability. Of the other informational areas that were reviewed as a part of Phase II, the information on methodology and spatial components indicated that the most common methodology included modeling of some sort and most commonly was spatially-explicit. Only 9 of the 30 assessed CCVAs completed a non-spatially-explicit assessment of vulnerability. The majority of these 9 assessments relied on interviews as a key part of their methodology.

Discussion

Before beginning this review, it was expected that CCVAs for ecosystems were not using frameworks to guide their assessments. As it turns out, more than half (56.7%) used one or more frameworks when crafting their assessments. However, the bigger surprise was the number of different frameworks and different attributed papers or subsidiaries credited as the source of these frameworks. The outcome was a lack of coordination or correlation in which frameworks were guiding these assessments. In some cases, papers that were cited as providing the framework for the target assessment actually further cited other frameworks in their papers. In general, that doesn't necessarily mean that these assessments are viewing vulnerability in different ways. In fact, the most common originator of a CCVA framework referenced was the IPCC. They have overtime released multiple operational definitions of vulnerability. The

CCVAs that cited vulnerability cited either the 2001 Working Report on Climate Change, the 2007 Assessment Report (AR4) or the 2014 Assessment Report (AR5).

What was found was that it was common that even if a paper went on to use another theoretical framework, they used the IPCC as reference for their definition of vulnerability. The definition for Vulnerability provided in the annexes of these reports is different between each publication.[58] Most commonly used are the AR4 and AR5 definitions which describe Vulnerability as "The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity" and "The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt," respectively.[59,60] This is important because the results of this paper show that the IPCC is the most common reference for the operational definition of vulnerability and resulting framework. However, since there have been multiple definitions overtime, some of the authors of the reviewed CCVAs have cited this inconsistency as a cause of difficulty in ascertaining the correct guidance on how to define and operationalize vulnerability.[61]

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[58] Intergovernmental Panel on Climate Change. "Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change." Geneva, Switzerland, 2007.
[59] Ibid.
[60] Intergovernmental Panel on Climate Change. "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change." Geneva, Switzerland, 2014.
[61] Gautam, Mahesh R., Karletta Chief, and William J. Smith Jr. "Climate change in arid lands and Native American socioeconomic vulnerability: The case of the Pyramid Lake Paiute Tribe" *Climatic Change 120, no. 3* (2013): 585-599

This difficulty in defining vulnerability was a common theme in the reviewed Ecosystem-Specific CCVAs, even for those who did not use the IPCC as guidance. CCVAs reviewed as a part of this paper mentioned, among other emerging issues, the trouble with defining vulnerability, the lack of agreement over which framework to use, and the trouble with applying methods for one area and its specific adaptation issues to another area.[62,63,64] While it was believed that the major problem facing the success of Ecosystem-Specific CCVAs might be the lack of framework to guide assessment, in fact it seems that this is only one issue in a chain of connected problems. Even when a framework is being used to guide assessment, the project still has to make a choice on how to define vulnerability and its components and which framework both best suits this definition and need of the study. The framework that is chosen needs to be sufficiently general to account for differences in study design but provide enough information so that components may be weighted in a similar fashion.

Some of the reviewed assessments referenced literature and other studies that have provided theoretical guidance but the reviewed assessment ultimately decided against using that theoretical framework. This makes it seem as though there may be an issue translating guidance from leaders such as the IPCC into an actionable methodology. This may be the case especially when looking on an Ecosystem-Specific scale where interactions between ecosystem members and features may make the task of reaching a representative vulnerability score difficult without more explicit guidance on weighting and connection of components of vulnerability. Further study on this question could take the form of post-assessment interviews to those who complete

[62] Esteves, Tashina, Darshini Ravindranath, Satyasiba Beddamatta, K. V. Raju, Jagmohan Sharma, G. Bala, and Indu K. Murthy. "Multi-Scale Vulnerability Assessment for Adaptation Planning." *Current Science 110, no. 7* (2016): 1225–39. doi:10.18520/cs/v110/i7/1225-1239.
[63] Gautam et. al.. "Climate change in arid lands," 595.
[64] Vanneuville, Wouter and Beate Werner. "Water resources in Europe in the context of vulnerability" EEA Report No 11/2012. Luxembourg, 2012. doi:10.2800/65298.

CCVAs and inquire about the reasoning behind the decision to not use a theoretical framework, if the reasoning was not included in the discussion portion or methods.

This assessment also highlighted that the definition of vulnerability, a theoretical framework, and a vulnerability formula are indeed three separate things. Many assessed CCVAs began by crediting one paper or group (such as the IPCC) as their source for understanding vulnerability in the context of their study. However, this did not always translate directly to the framework that they chose. Furthermore, the formula may go on to take the framework chosen by the author and define the specific relationship between components and vulnerability in a way not included in either the framework or operational definition. This was believed to be the case and results have shown this to be true. This is actually good news for adaptation practitioners in that it suggests there can be agreement on operational definitions and theoretical framework and still open-up the methodology and formulaic weighing of components to get a vulnerability score. This would address the need for a framework which is well recognized and mentioned specifically as a need by CCVAs in this assessment.[65] It would also address the worry that each area's specific adaptation needs warrant a flexible assessment methodology.[66]

Another result of this review is the number of assessments that were characterized under Phase I in the resulting 3 groups. This data showed that the majority of publications were non-CCVAs even in repositories like CRAVe and Climate-ADAPT specifically marketed as hosting CCVAs. Phase I returned a lot of scientific papers or methodology papers that discussed how or why to do a CCVA. There were also miscellaneous papers that discussed climate risk, disaster risk, flooding impacts, or other climate related topics but weren't actual CCVAs. This meant that

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[65] Lee, Calvin. K., Clare Duncan, Harry J. F. Owen, and Nathalie Pettorelli. "A New Framework to Assess Relative Ecosystem Vulnerability to Climate Change." *Conservation letters* 11, no 2. (2017).

[66] Norway Ministry of the Environment. "Adapting to a changing climate: Norway's vulnerability and the need to adapt to the impacts of climate change." Official Norwegian Reports NOU 2010: 10, 2010.

the Other category was the largest for every database/repository tested. This suggests that a better organization and publication of CCVAs could perhaps further elevate case studies and make them more available for public consumption.

Of the publications that were categorized as either Ecosystem-Specific or Species-Specific there was a difference between the breakdown of groups for CRAVe vs the other two databases. Both the Climate-ADAPT and Catalyst databases showed between 56%-63% of Other studies and showed between 13%-15% Species-Specific CCVAs. This is in comparison with 45% Species-Specific CCVAs from the CRAVe database. It is believed that this is due to the fact that in the U.S., in the community of conservation work, species of concern are more often the target of vulnerability assessments than the assessment of ecosystems or areas.[67] This is in part due to the need historically to look at species health and vulnerability in the context of human actions or proposed policy.[68] Domestic environmental policies like the Endangered Species Act require a thorough understanding of existing vulnerability in order to list a species as endangered or threatened. While vulnerability assessments done in the context of climate change has l the number of stakeholders interested in assessing vulnerability, the conservation community has the advantage of species-specific framework in place.

The results from the international database, Climate-ADAPT, resembled the results from the peer-reviewed literature database. While it may be because the filtering of results from a targeted database like Climate-ADAPT for CCVAs only was not sufficient to return targeted results. Or, it could suggest that outside of the U.S. there is more CCVAs looking at the effects of climate change on ecosystems and areas. The Phase I results suggests that perhaps outside of

[67] Glick, Patricia, Bruce A. Stein, and Naomi A. Edelson. "Scanning the Conservation Horizon : A Guide to Climate Change Vulnerability Assessment". National Wildlife Federation: 2011, 24. https://repository.library.noaa.gov/view/noaa/10088.
[68] Glick and Stein, "Scanning the Conservation Horizon," 25.

the US there are more CCVAs being done in an ecosystem-specific context that balance the results to the levels seen on strictly peer-reviewed scientific database. This would match with the finding that while Climate-ADAPT and Catalyst had similar results in total percentage of publications showing a species-specific scope, the Climate-ADAPT database had 31% of its publications marked as Ecosystem-Specific which is more than double the 13% marked as species specific. This compared to 15% (species) and 22% (ecosystem) in the Catalyst database. If publications from the EU and other areas are pushing up the number of Ecosystem-Specific results for the peer-reviewed literature database and the US results are pushing up the number of Species-Specific results, this could explain why the numbers are closest in the Catalyst database. Recognizing that the numbers are also the most diluted with the highest percentage of non-related publications.

This review showed that some assessments did use well-recognized existing guides for CCVAs. Guides in this context are published guidance documents that include both a framework and a methodology for completing a CCVAs. Well-recognized refers to its inclusion in a compiled manual of available strategies for completing CCVAs and case studies put together by USFWS.[69] This guide indicates that there are a few methodologies and frameworks for CCVAs that have a backing by conservation science leaders.[70] It is believed that while the number of assessments that used one of these methods was small in the representative study, there are a wide number of assessments that have used a guided format. These emerging guides have their strengths and weaknesses for different assessment scopes and in the scope of ecosystem-specific

[69] Johnson, Kurt, A. "Climate Change Vulnerability Assessment Toolbox" 1.
[70] Ibid, 4.

tools, there are only 4 mentioned.[71] Continued development publication of these guides and associated tools may continue to expand their use in future assessments.

A major question that is left unanswered in the context of this paper is whether a framework has an impact on the quality of the outcome of the vulnerability assessment. What was addressed here was whether or not assessments shared similar approaches, which has been indicated as a road-block for integration of results and duplication of study.[72] The data gathered in the completion of this review points to a lack of cohesion in approach and does show some indication that there is a correlation between lack of framework and lack of methodology. Furthermore, frameworks that use a formula for vulnerability were more likely to use an approach that used climate modeling and spatially-explicit data. This paper makes no comment on the relative success of one methodology over another but does recognize the correlations seen between framework use and methodology design. Future study should look at the relative success of assessments that are guided by framework if performance-based outcomes of CCVAs are to be reviewed.

This paper expands on the request by the UNFCCC Subsidiary Body for Scientific and Technological Advice to institutionalize EbA, specifically in the context of Vulnerability Assessments.[73] The need for a framework for vulnerability assessments is also recognized in completed CCVAs such as the North Atlantic Coast Comprehensive Study.[74] In the final report's conclusions, it specifically identifies the need for a framework as a key next step.[75] Lessons learned from this paper could be used to further address the role of frameworks in CCVAs

[71] Johnson, Kurt, A. "Climate Change Vulnerability Assessment Toolbox" 10.
[72] Lee et al. "A New Framework."
[73] UNFCCC, "Report on the Technical Workshop." 19.
[74] Bridges et al. "Use of Natural and Nature-Based Features (NNBF)," 3.
[75] Ibid, 3.

specifically in an ecosystem concept. The lack of any trends in use of an existing theoretical framework, outside that provided by the IPCC, suggest that more attention is needed on reviewing existing frameworks and bringing stakeholders together to agree on accepted and recommended options for guiding CCVAs. Bringing some top-down management to the practice of evaluating the vulnerability of areas to climate change can serve as a step in the right direction for producing more useful CCVAs for both conservationists and other stakeholders alike.

Appendix A

Table 1

		Name	Lead Organization	Framework	Fomula	Assessed by Wh	Methodology	Spatial or no	Assessment Area	Components
CRAVe	1	A research and decision support framework to evaluate sea-level rise impacts in the northeastern U.S.	USGS	Self	none	Self	Bayesian network	Spatially Explicit	Northeast Coast	SLR
	2	Ecosystem Vulnerability to Climate Change in the Southeastern United States	USGS	Costanza et al. 2016	E+S=I , I+A=V	Self	Literature Review	Non	Multi-Ecosystem	Multi-factor
	3	Assessing Climate-Sensitive Ecosystems in the Southeastern United States	USGS	Glick et al.	E+S=I , I+A=V	Workshop	Self	Spatially Explicit	SEAFWA region	Multi-factor
	4	Assessing Climate-Sensitive Ecosystems in the Southeastern United States - Phase II	USGS	HCCVI	I+A=Res , S+Res=V	Workshop	HCCVI	Spatially Explicit	SEAFWA region	Multi-factor
	5	Assessing Climate Change Effects on Natural and Cultural Resources of Significance to Northwest Tribes	Northwest CSC	none	none	Self	Interviews	Non	Tribal Areas	Multi-factor
	6	Predicting Sea-Level Rise Vulnerability of Terrestrial Habitat and Wildlife of the Northwestern Hawaii	USGS	none	none	Self	hydrodynamic model	Spatially Explicit	Northwest Hawaiian Islands	SLR
	7	Changes to watershed vulnerability under future climates, fire regimes, and population pressures	USGS	none	none	Agecncy Collaboration	Multi Averaging	Spatially Explicit	Watersheds	Fire
	8	Gulf Coast Vulnerability Assessment	Gulf Coast Prairie LCC	Reece and Noss 2014	E+S=I , (I+A)/2=V	Committee	Standardized Index of Vulnerability and Value Assessment	Spatially Explicit	Gulf Coast	Multi-factor
	9	Forest Ecosystem Vulnerability Assessment and Synthesis for Northern Wisconsin and Western Upper Michigan	USDA	Swanston and Janowiak 2012	I+A=V	Committee	Expert ranking using modeling data	Spatially Explicit	Northern Wisconsin and Western Upper Michigan	Multi-factor
	10	Climate change in arid lands and Native American socioeconomic vulnerability	Desert Research Institute	IPCC 2001 and Füssel 2007	V=*f*(E,S,A)	Self	Interviews	Non	Pyramid Lake Paiute Tribe Region	Multi-factor
Climate ADAPT	1	Water resources in Europe in the context of vulnerability	European Environment Agency	Metzger et al. 2006, and Uyttendaele et al. 2011.	E+S=I , I+A=V	Self	modeling	Spatially Explicit	Europe	Multi-factor
	2	Adaptation to Climate Change in Europe and Central Asia Agriculture	The World Bank	Australian Government 2005	E+S=I , I+A=V	Workshop	none	non	Europe and Central Asia	Multi-factor
	3	Adaptation in water and coastal areas in Puglia, Italy	Centro Euro-Mediterraneo sui Cambiamenti Climatici	UNISDR 2009 and by IPCC 2014	H+E+VA=RR	Workshop	Interviews + modeling	Spatially Explicit	Puglia, Italy	Water resources
	4	Report on Climate Analysis and Vulnerability Assessment Results in the Pilot Region (Sardinia Region)	ISPRA	IPCC 2014 and others	V= S(weighted) +A(weighted) / weight1+ weight2	Self	modeling	Spatially Explicit	Sardinia	Multi-factor
	5	Climate change vulnerability and ecosystem-based adaptation measures in the Carpathian	ECORYS, ECNC, Grontmij and WWF-DCP	Self	IA+AA=VA ** used V=E+S+A in 1st	Workshop + Self	modeling	Spatially Explicit	Carpathian region	Multi-factor
	6	An Assessment of Climate Change Vulnerability in Albania's Power Sector	Energy Sector Management Assistance Program	Willows and Connell, 2003	V=R	Self	risk register + cost benefit	Spatially Explicit	Albania	Multi-factor
	7	Adapting to a changing climate, Norway's vulnerability	Norway Ministry of Environment	IPCC 2007	V=E+S+A	Committee	modeling	Spatially Explicit	Norway	Multi-factor
	8	ICPDR Climate Change Adaptation Strategy 2018	International Commission for the Protection of the Danube	Self - Adapted from IPCC 2007 and IPCC 2014	V+E+H=R , R=I , I=C+S and I=E	Self	CLIMSAVE - Integrated	Spatially Explicit	Danube River Basin	Multi-factor
	9	Climate Resilient Infrastructure: Preparing for a Changing Climate.	UK Department for Environment Food and Rural	none	none	Workshop	Interviews and Literature Review	Non	UK Infrastucture	Multi-factor
	10	Climate Change Vulnerability Mapping for the Nordic Region	CARAVAN	Preston and Stafford-Smith (2009)	V = [ES + (1–AC)] / 2	Workshop	Modeling	Spatially Explicit	Nordic Countries	Multi-factor

Appendix A continued

Catalyst	1	Spatially identifying vulnerable communities to climate change impact in South Australia	The University of Adelaide	Self	V=E+S+A	Self	SLR + socio-economic indicators = hot spots	Spatially Explicit	South Australia	Multi-factor
	2	Mapping Climate Change Vulnerability and Impact Scenarios	UNDP	Self	V = ExS–A	Self	Modeling	Spatially Explicit	Europe	Multi-factor
	3	A New Framework to Assess Relative Ecosystem Vulnerability to Climate Change	Zoological Society of London	Self	H (E+S+A) + H (E+S+A) = V	Self	Hazard Driven with spatially explicit proxies	Spatially Explicit	Mangrove Forests	SLR + Storm
	4	Climate change vulnerability assessment of forests in the Southwest USA	USDA	Glick et al.	V=E+S+A	Self	Spatial modeling + literature review	Spatially Explicit	Southwest US Forests	Multi-factor
	5	Climate change vulnerability assessment for the uranium supply chain in Australia	Monash University, Melbourne, Australia	Pearce et al. 2009, definition from IPCC, 2001–2007, Füssel and Klein 2006, Füssel 2007	V=*f*(E,S,A)	Self	Interviews	Non	Australia (uranium mining)	Multi-factor
	6	Multi-scale vulnerability assessment for adaptation planning	Centre for Sustainable Technologies	Self	none	Self	Indicator-based Vulnerability Index	Non	Karnataka, India	Multi-factor
	7	Assessment of vulnerability to climate change using a multi-criteria outranking approach with application to heat stress in Sydney	University of Sydney	Self	V=*f*(I1,I2,I3)	Self	IBVA	Spatially Explicit	Sydney, Australia	Multi-factor
	8	Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure	Virginia Department of Transportation	Self	V=*f*(E,S,A)	Self	IBVA	non	Hampton Roads	Multi-factor
	9	Linkages between human health and ocean health	Kawerak, Inc	IPCC 2007 and Ford et. al. 2010	V=*f*(E,S,A)	Self	Workshop + interviews	non	Alaska's Bering Strait Region	Multi-factor
	10	Income Inequality and Urban Vulnerability to Flood Hazard in Brazil	U.S. Forest Service	Schneiderbauer and Ehrlich 2006	V=(HxE)/A	Self	Mixed-Effects Modeling	Spatially Explicit	Brazil	Multi-factor

Formula Key: V = Vulnerability; A = Adaptive Capcity; E = Exposure; S = Sensitivity; Res = Resilience; H = Hazard; I = Impact; VA = Vulnerability Assessment; RR = Relative Risk; IA = Impact Assessment; AA = Adaptation Assessment; C = Climate Processes; S = Socioeconomic Processes; E = Emissions and Land change; I = Indicator; X = Other Factors

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